

Jet Production in DIS at NLO

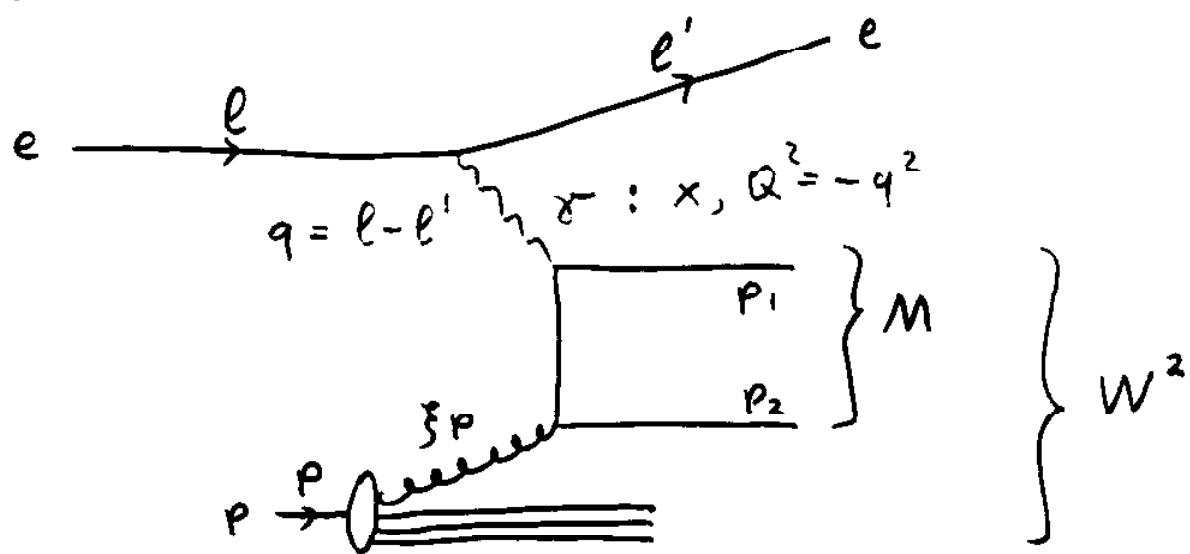
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DIS 97

- Introduction: dijets at HERA
- NLO corrections to dijet production
- Comparison of jet algorithms
and recombination schemes
- Forward jets and BFKL

Dijet Production in DIS



Scaling variables

$$x = \frac{Q^2}{2p \cdot q} \quad (\text{Bjorken } x)$$

$$y = \frac{p \cdot q}{\ell \cdot q} = \frac{Q^2}{x s}$$

M : c.m. energy in γ^* -parton system

W : produced hadronic mass

ξ : momentum fraction of incident parton

$$\xi = x \left(1 + \frac{M^2}{Q^2} \right)$$

p_1, p_2 : jet momenta (at LO)

Typical cuts and cross sections at HERA

$e^- p$ & $e^+ p$ collisions at

$$E_e = 27.5 \text{ GeV}, \quad E_p = 820 \text{ GeV}, \quad \Rightarrow \sqrt{s} = 300 \text{ GeV}$$

integrated luminosity delivered by HERA

$$\int L dt = 20 - 25 \text{ pb}^{-1}$$

analysed for dijet events

e.g. H1 : 2 pb^{-1} out of 14 pb^{-1} taken.

expected by ~ 2001 (after luminos. upgrade)

$$\sim 1000 \text{ pb}^{-1}$$

compar to typical dijet cross section

Select DIS (as opposed to photoproduction)

$$40 \text{ GeV}^2 < Q^2 < 2500 \text{ GeV}^2$$

↑
eliminates Z-exchange

lepton cuts:

$$E(\ell') > 10 \text{ GeV}, \quad \gamma > 0.04$$

$$|\eta(\ell')| < 3.5$$

jets (cone scheme)

$$\Delta R = \sqrt{(\Delta\gamma)^2 + (\Delta\varphi)^2} > 1$$

$$p_{Tj} > 5 \text{ GeV}, \quad |\eta(j)| < 3.5$$

\Rightarrow dijet cross section at LO

$$\sigma_{jj}^{LO} = 1100 \text{ pb}$$

\Rightarrow few $\cdot 10^3$ events at present

Topics to be studied

- Measure $\alpha_s(\mu_R^2)$ \rightarrow Wednesday

$$\sigma \left(\text{Diagram} \right) \sim \alpha_s$$

- Directly measure gluon distribution fit
 \rightarrow Thursday

$$\text{Diagram} \sim g(x, u_F^2)$$

- Forward jets and BFKL dynamics
 \rightarrow afternoon
- polarized gluon pdf's ?

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•

Need NLO QCD corrections

NLO corrections for $e p \rightarrow e jjX$ in DIS

Feynman diagram for LO approximation:

LO:

An incoming electron (e) interacts with a proton (p) to produce an electron (e) and a jet (j). The interaction point is indicated by a wavy line.

A hand-drawn diagram showing a horizontal line segment labeled 'e' at both ends. From the right end, a vertical line segment labeled 'j' descends. From the top of this vertical segment, a diagonal line segment labeled 'g' extends upwards and to the right. From the bottom of the vertical segment, another line segment labeled 'j' extends downwards and to the right. From the right end of the original horizontal line, a wavy line segment labeled 'p' descends, eventually meeting the vertical line labeled 'j' at its lowest point.

NLO:

Previous calculations:

PROJET

DISJET

Grundenz

Brodkorb, Mirkes

semi analytic approach:

→ JADE jet definition scheme only

→ very restricted set of distributions & cuts

Two new calculations

Both us flexible NLO Monte Carlos

MEPGET Mirkes, Zeppenfeld

uses s_{\min} method of Siele & Glover

DISENT Catani, Seymour

uses subtraction method; available
since Oct. 96

agreement at 3% level

Physics discussion below is based
on MEPGET results.

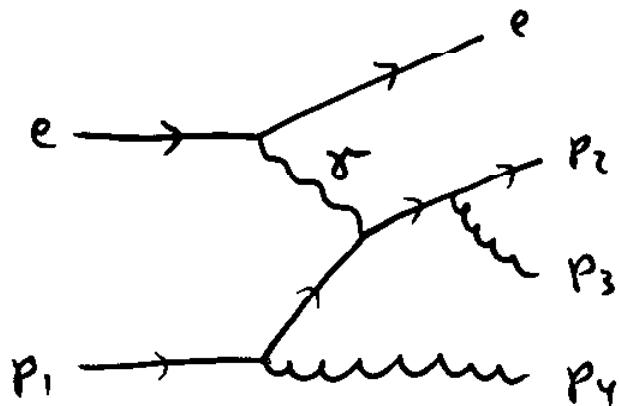
MEPJET - DISENT comparison

(M. Seymour & D.Z.)

- K_T scheme with $\bar{E}_T^2 = Q^2$, $Y_{cut} = 1$
- $Q^2 > 40 \text{ GeV}^2$
- $\lambda = 1/(3\pi)$, no Z -exchange
- MRS D₋¹
- $m_R = m_F = R$, $\beta! \exp x_S$, $\Lambda_S = 230 \text{ MeV}$

	DISENT	MEPJET	
1j LO	21.958 ± 0.016	21.954 ± 0.015	n!
2j LO	395.6 ± 1.5	393.2 ± 0.9	p!
3j LO	33.0 ± 0.5	32.5 ± 0.2	p!
2j NLO	501 ± 7	559 ± 6	p!
with $p_{Tj} > 5 \text{ GeV}$, $ \eta_j < 3.5$			
2j LO	339.0 ± 0.4	337.5 ± 0.4	p!
2j NLO	463 ± 8	480 ± 5	p!

Our approach: s_{\min} phase space slicing method
of Glover & Giele



$$\sigma_3 = \infty$$

(soft + collinear)
region

3 parton cross section

$$\sigma_3 (2 p_i \cdot p_j > s_{\min}) \quad \text{finite}$$

"2 parton" cross section

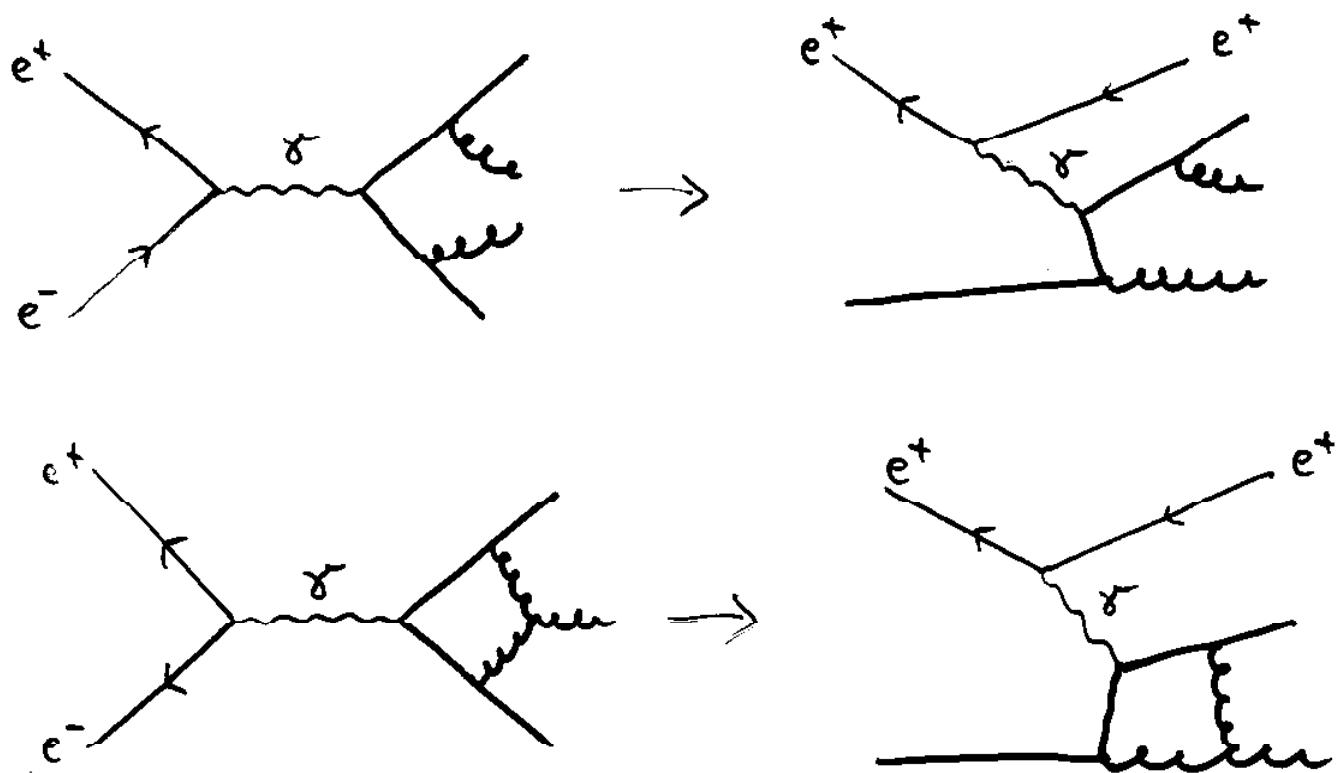
$$\sigma_2 = \sigma_{\text{Born}} + \underbrace{\sigma_{\text{virtual}} + \sigma_3 (2 p_i \cdot p_j < s_{\min}) - \sigma_{\text{factoriz}}}_{\text{finite}}$$

s_{\min} small enough: soft + collinear approximations allowed; divergent terms

$$\frac{d\sigma}{d\text{divergent}} \sim \frac{d\sigma}{d\text{Born}} * \left(\frac{1}{\varepsilon}, \frac{1}{\varepsilon^2} \right)$$

cancel divergencies at individual 2 parton phase space point

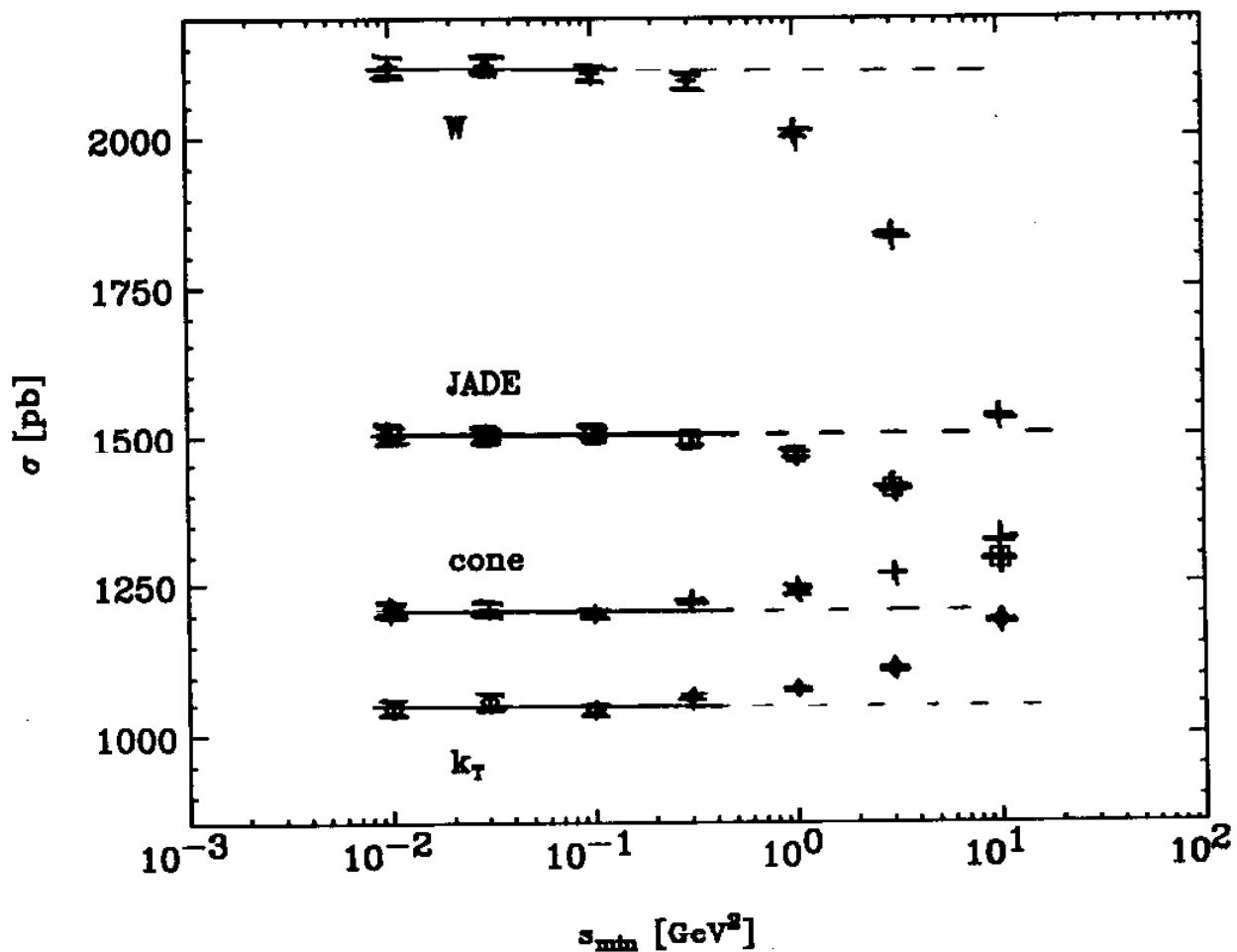
Analytic part of the calculation is straight forward: use known results for NLO QCD corrections to $e^+e^- \rightarrow 3\text{jets}$ (e.g. Kramer et al.)



crossing is performed by using NLO crossing functions of Giele, Glover, Kosower

Test of calculation :

s_{\min} independence of result
for small s_{\min}



Full NLO Monte Carlo program

M E P J E T

- any jet definition scheme JADE
cone
 $K_T \dots$
- arbitrary experimental cuts
- package includes
 - $e p \rightarrow e j(j) X$ (DIS) at LO & NL
 - $e p \rightarrow e jj(j) X$ at NLO & LO
 - $e p \rightarrow e jjj X$ at LO
 - $e jjjj X$ at LO
- available upon request from
 Erwin Mirkes :
 mirkes@ttxnxl.physik.uni-karlsruhe.de
 D.Z. : dieter@pheno.physics.wisc.edu

New in version 2.0

- b and c-quark mass effects at LO
- τ, Ξ interference at LO
" " at 1j NLO
(bug in 2.0, corrected in 2.1)
- 4 jet final state

Jet definition schemes (parton level)

- cone scheme

recombine partons/clusters with

$$\Delta R < 1$$

call recombined clusters jets if

$$p_{Tj}^{\text{lab}} > 5 \text{ GeV}, \quad |\gamma_j| < 3.5$$

- K_T scheme

defined in Breit frame, i.e. frame
in which

$$\gamma^* : q = (0, 0, 0, -2 \times E) \Rightarrow Q^2 = 4 \times^2 E^2$$

proton : $p = (E, 0, 0, E)$

recombine partons i, j with

$$M_{ij}^2 = 2 \min\{E_i^2, E_j^2\} (1 - \cos \theta_{ij}) < E_T^2$$

recombine parton i with beam jet

$$2 E_i^2 (1 - \cos \theta_i) < E_T^2$$

Hard scattering scale for k_T -scheme

$$E_T^2 = 40 \text{ GeV}^2$$

Resulting clusters = jets

• W scheme

Consider partons : p_i

proton remnant: $p_r = (1-\gamma)p$

Recombine pair with smallest

$$M_{ij}^2 = (p_i + p_j)^2 < \gamma_{\text{cut}} W^2$$

Final clusters (\neq remnant) = jets

Here: $\gamma_{\text{cut}} = 0.02$

• JADE scheme

variant of W-scheme with

$$M_{ij}^2 = 2 E_i E_j (1 - \cos \theta_{ij}) < \gamma_{\text{cut}} W^2$$

i.e. neglect masses²: p_i^2, p_j^2

Here: $\gamma_{\text{cut}} = 0.02$

Recombination schemes

Determine cluster 4-momentum p_{ij} from component 4-momenta p_i, p_j

- E-scheme

$$p_{ij}^{\mu} = p_i^{\mu} + p_j^{\mu}$$

- $E\phi$ -scheme

$$p_{ij} = (p_i^0 + p_j^0, \beta(\vec{p}_i + \vec{p}_j))$$

with β such that $p_{ij}^2 = 0$

- p-scheme

$$p_{ij} = (\frac{1}{\beta}(p_i^0 + p_j^0), \vec{p}_i + \vec{p}_j)$$

with β such that $p_{ij}^2 = 0$

Two-jet inclusive cross sections (in pb)
for the four jet algorithms

	Cone	K_T	W	JADE
L0	1107	1067	1020	1020
NLO (E)	1203	1038	2082	1507
NLO (E0)	1232	1014	1438	1387
NLO (p)	1208	944	1315	1265

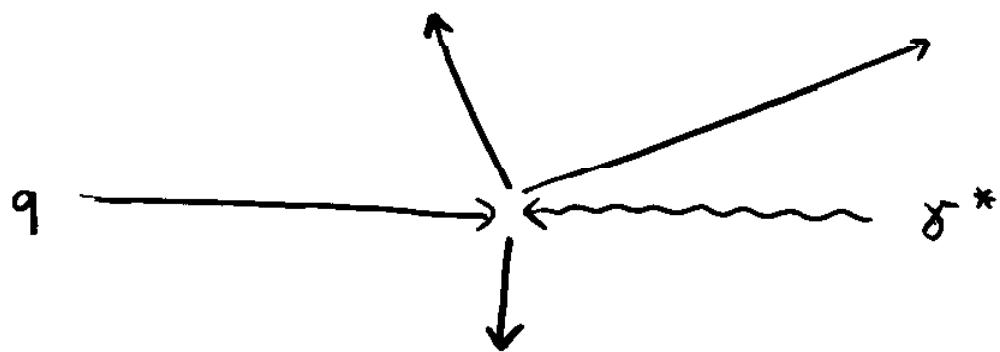
⇒ Large K-factor, strong recombination scheme dependence for W and JADE

Recombination scheme effects are only modeled at L0

⇒ Variation with recombination scheme is subject to large $\mathcal{O}(\alpha_s^3)$ corrections

⇒ Large theory uncertainty for JADE & W

Source of recombination effects : mass of reconstructed jets





W and JADE scheme recombine relatively soft, well separated partons to jets

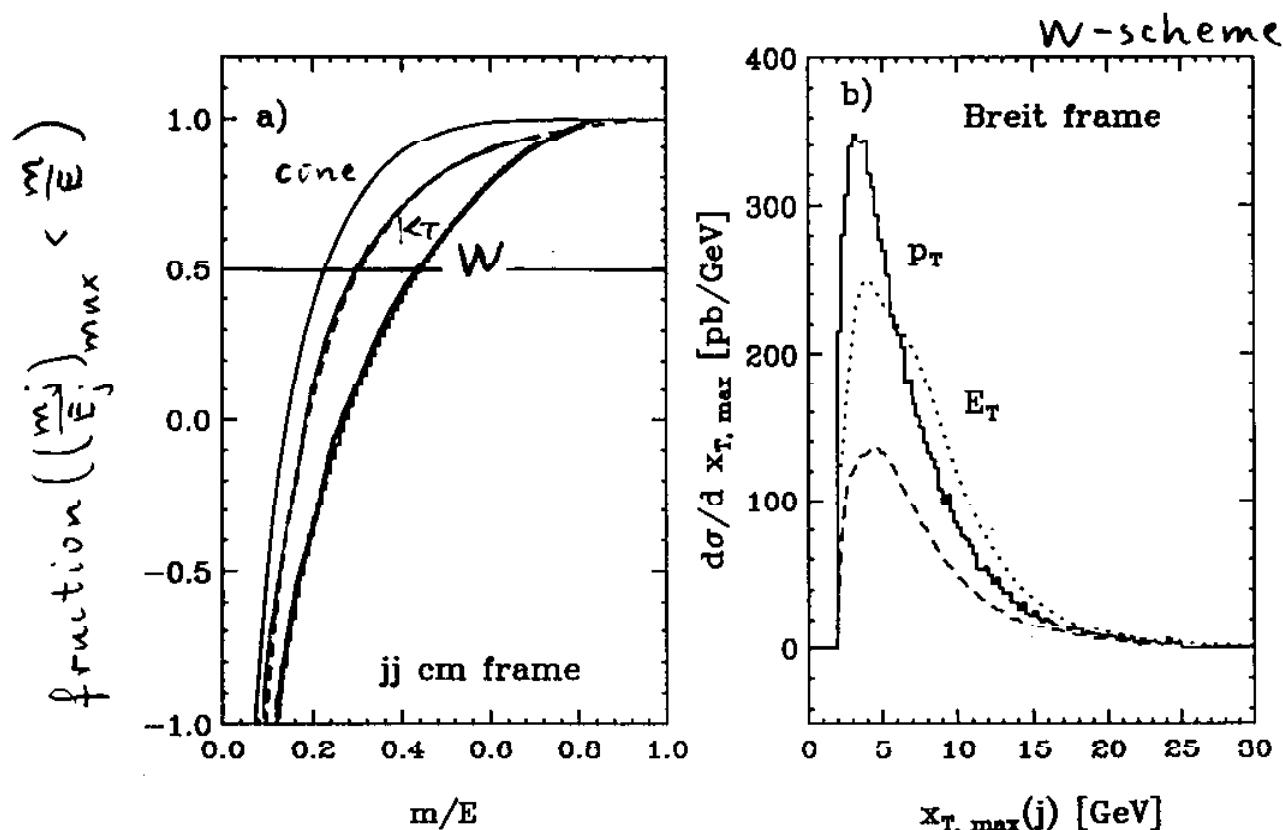
\Rightarrow jet has sizable mass $\sqrt{p_z^2}$

Large mass helps to survive cut

$$(p_1 + p_2)^2 = 2p_1 \cdot p_2 + p_2^2 > Y_{\text{cut}} W^2$$

Problem: NLO jets do not correspond to hard parton with some soft and collinear gluon radiation.

Importance of mass effects



medium (m_j, E_j) _{max}:

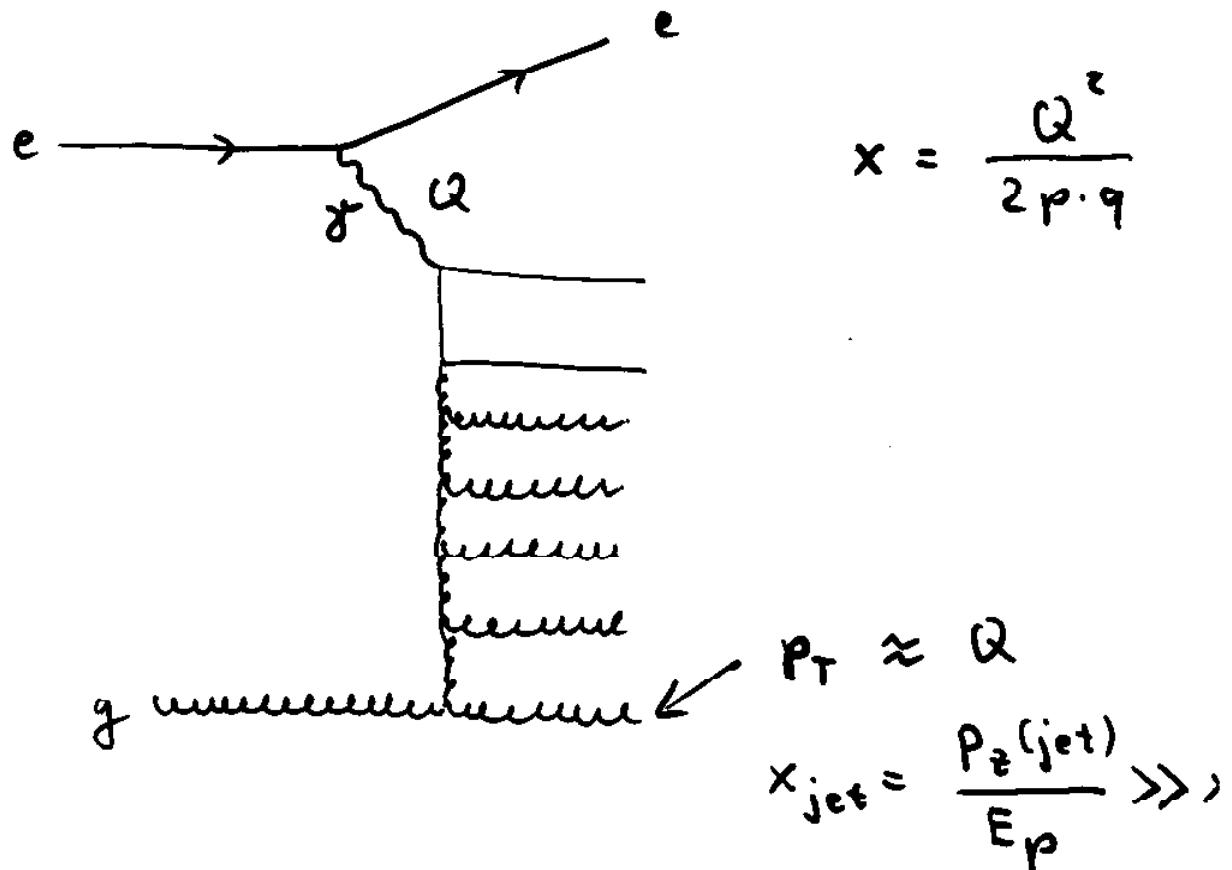
Cone scheme: 0.22

k_T scheme: 0.30

W scheme: 0.44

Forward jets and BFKL dynamics

Isolate BFKL dynamics (gluon ladders) by tagging forward (Mueller-Navelet) jet



BFKL prediction

$$\frac{\sigma_{\text{BFKL}}(x \ll x_{\text{jet}})}{\sigma_{\text{fixed order QCD}}} \sim \left(\frac{x_{\text{jet}}}{x} \right)^{\alpha_P - 1} \gg 1$$

Fixed order QCD is "background"

Fixed order QCD contribution: at $O(\alpha_s^2)$

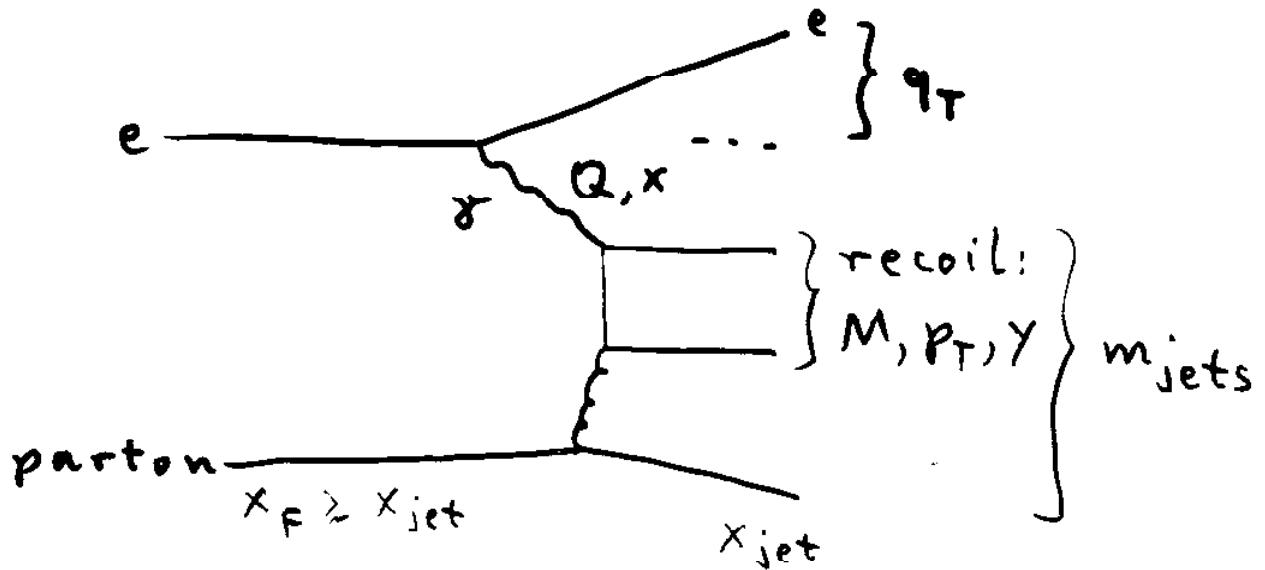
- 1 (massless) parton in final state
at 2 loops

forbidden by $x_{\text{jet}} \gg x$

- 2 partons at 1 loop
 - 3 partons at tree level
- } same as
 $e p \rightarrow e jj X$
at NLO

\Rightarrow MEGJET can determine 1-jet inclusive forward jet cross section at full $\mathcal{T}(\alpha_s^2)$

Kinematic constraints



$$(m_{\text{jets}})^2 = \hat{s}_{\gamma, \text{parton}} = Q^2 \left(\frac{x_F}{x} - 1 \right) \gg Q^2$$

$$\approx M^2 + 2x_{\text{jet}} E_p \sqrt{M^2 + p_T^2} e^{-Y} \gg Q^2$$

$$p_T = |\vec{p}_{T,\text{jet}} + \vec{q}_T| \text{ bounded} \Rightarrow M \text{ large}$$

No colinear singularity for partons in γ^* -direction

- there are additional jets in recoil system
- cross section calculable as $\sigma_{zj, \text{incl.}}^{\text{NLO}}$

Kinematics forces existence of additional jets

Properties of hardest "recoil jet"

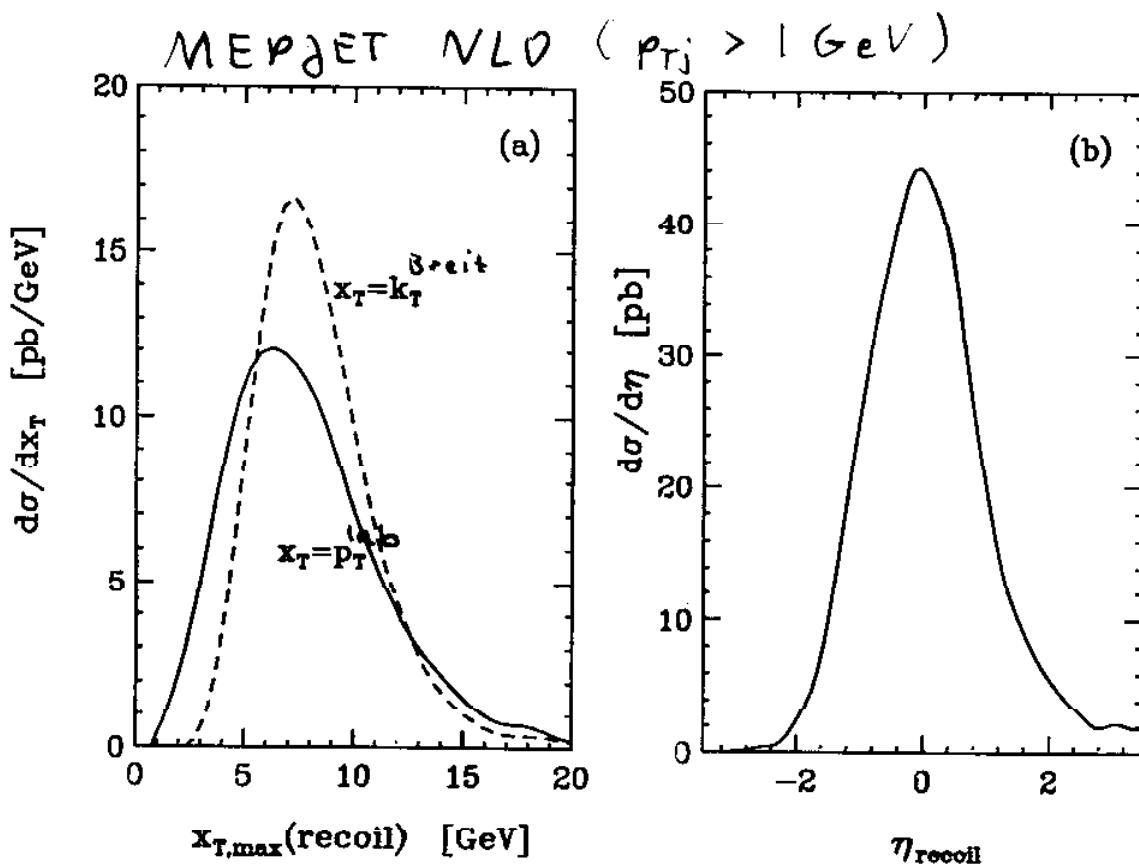
cone scheme

H1 selection cuts

$$x < 0.004$$

$$x_{\text{jet}} > 0.05, \rho_T^{\text{jet}}(\text{forward}) > 5 \text{ GeV}$$

$$2.5 < \rho_T^{\text{jet}} / Q^2 < 4$$



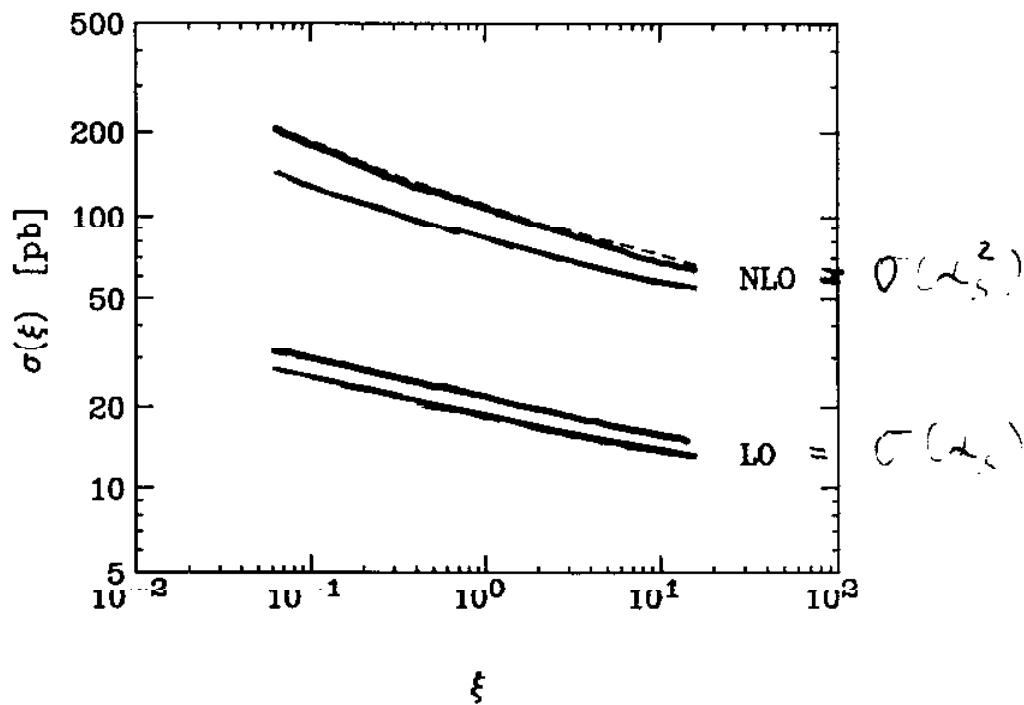
Uncertainties of fixed order results

- strong scale dependence

$$\sigma_R^2 = \sigma_F^2 = \begin{cases} \xi \left(\frac{1}{2} \sum k_T^3 \right)^2 \\ \xi Q^2 \end{cases}$$

- Large effective K factor

$$K \approx 4 - 5$$



ξ

3-parton final states dominate

$\Rightarrow O(\alpha_s^2)$ cross section is effectively LO

Does $\sigma(\mathcal{O}(\alpha_s)) \ll \sigma(\mathcal{O}(\alpha_s^2))$ persist
at order α_s^3 ?

with forward jet

$$P_T^{\text{lab } B}, P_T > 4 \text{ GeV}$$

without

$$K_T^B > 4 \text{ GeV}$$

$$P_T^B, P_T^{\text{lab}} > 4 \text{ GeV}$$

$\Gamma(\alpha_s): 2j$ 18.9 pb 22.4 pb 2120 pb

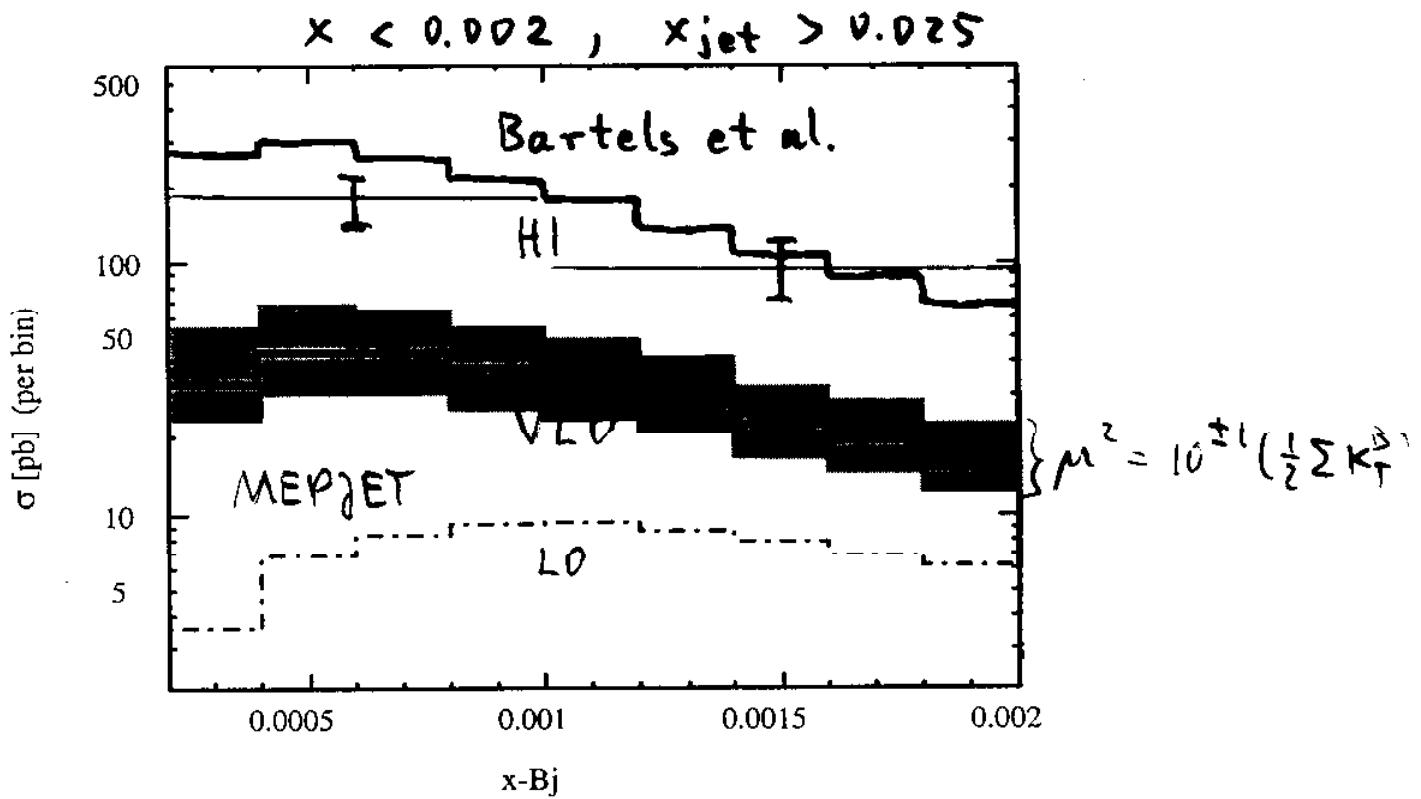
$\Gamma(\alpha_s^2): 2j$ 69.0 pb 65.8 pb 2190 pb

$3j$ 4.8 pb 31.5 pb 210 pb

$\mathcal{O}(\alpha_s^3): 4j$ 2.8 pb 5.3 pb 22.3 pb

Comparison with

- BFKL calculation (Bartels et al, hep-ph/96042)
- H1 data (PL B356 (1995) 118)



Data show evidence for BFKL dynamics enhancement above NLO QCD

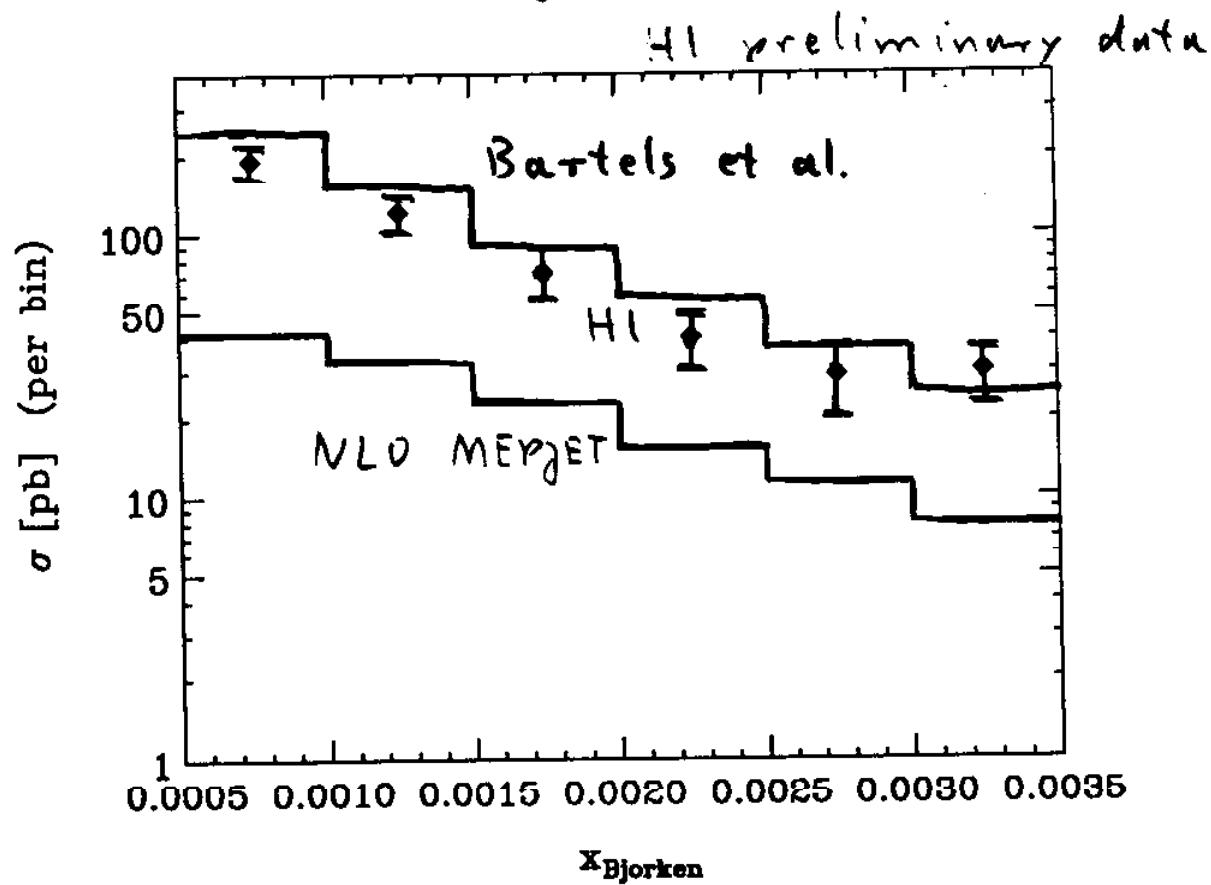
Comparison with 1994 H1-data

Forward jet with

$$p_{Tj} > 3.5 \text{ GeV}$$

$$E_j > 28.7 \text{ GeV} \Rightarrow x_{\text{jet}} > 0.035$$

$$0.5 < p_{Tj}^2 / Q^2 < 2$$



Evidence for $BFKL$ persists

Summary

NLO corrections to dijet production
in DIS now exist in the form of two
NLO Monte Carlo programs. DISENT
MEPYET

Large recombination scheme effects
and NLO corrections make the W and
JADE schemes unsuitable for NLO
QCD studies.

NLO QCD cannot explain rate of
forward jet events observed at HERA
→ evidence for BFKL effects.